

Relativistic Jets from X-ray binaries [★]

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Abstract. In this review I summarise the status of observational research into relativistic jets from X-ray binaries, highlighting four areas in particular: (i) How relativistic are the jets?, (ii) The disc: jet coupling, (iii) the nature of the underlying flat spectral component, and (iv) the relation between jets from black holes and those from neutron stars. I have attempted to discuss the extent of our (limited) physical understanding, and to point the way towards relevant new observational tests of the various phenomena.

1 Introduction

At the time of writing, some 200 – 250 X-ray binaries, systems in which a neutron star or black hole is accreting material from a companion star, are known. Approximately 20% of these sources have been detected at radio wavelengths, and in several cases high resolution radio observations have resolved this emission into jet-like structures, sometimes with components moving at relativistic velocities. All of these relativistic jets emit primarily via incoherent synchrotron emission from very high energy electrons spiralling in magnetic fields (although other emission mechanisms may contribute to the weak, flat spectral components which are sometimes observed). Detailed reviews of the synchrotron emission process and radio emission from X-ray binaries in general can be found in [26,24].

In this review I will not spend time discussing sources individually, but rather try to concentrate on areas in which the physics of what is occurring in general might be probed. This is due in part to detailed discussion of individual sources in previous reviews (e.g. [24,13,50,35]) and in part to a feeling that the jet mechanism is to a large degree independent of what is occurring beyond the inner parts of the accretion disc (leading to a disparate collection of binary systems with common jet characteristics).

I also have to stress that much of the following discussion has been heavily based upon discussions on the nature of AGN jets which have been ongoing for more than 20 years, and that many of the problems I am attempting to

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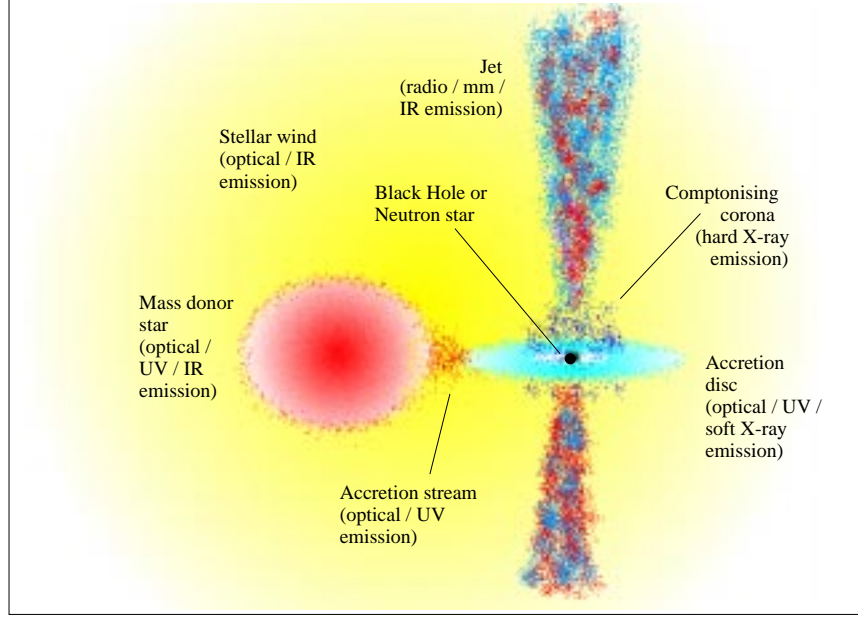


Fig. 1. A sketch of the various emitting regions in an X-ray binary, as we currently envisage them. The jet is believed to propagate from the inner accretion disc, more or less perpendicular to the binary plane.

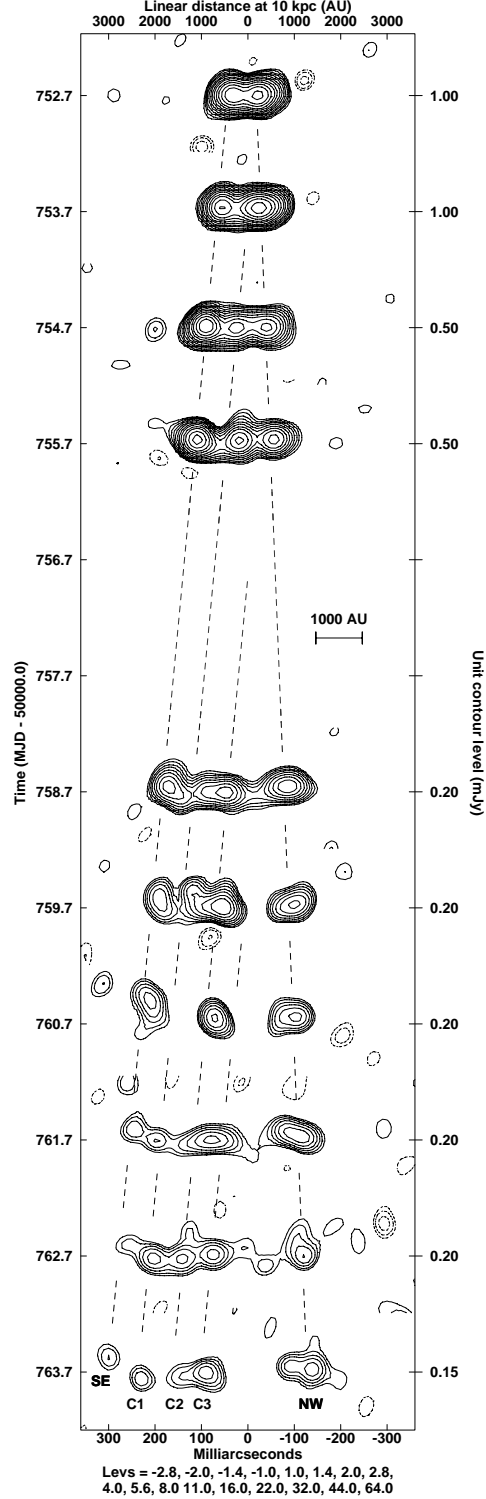
address were first recognised by the AGN community more than a decade ago.

Fig. 1 attempts to summarise our current ideas regarding where the different forms of radiation from an X-ray binary physically originate. The jets are believed to form close to the accreting compact object and to propagate in opposite directions away from the compact object along the symmetry axis of the inner accretion disc (although it may well be instead the rotation axis of the black hole, which in the case of GRO J1655-40 *may* be misaligned with the orbital axis by $\sim 15^\circ$ [37]). Fig. 2 is an example of *real* radio images of jets from which, combined with optical, infrared and X-ray flux monitoring (e.g. Figs 4 & 5), and a smattering of theory, we draw such inferences.

2 How relativistic ?

An important and obvious point to raise concerning the jets from X-ray binaries is *how* relativistic are the bulk motions ? This is a fundamental question for the theory and energetics of these systems, and is not as well constrained by observations as might be imagined (only SS 433, with $\beta = v/c = 0.26$ has a confidently determined velocity). For the MERLIN observations of GRS

Fig. 2. A sequence of ten epochs of radio imaging of relativistic ejections from the black hole candidate X-ray binary GRS 1915+105 using MERLIN at 5 GHz. The figure has been rotated by 52 degrees to form the montage. Contour levels increase in factors of $\sqrt{2}$ from the unit contour level indicated at the right hand side of each image. Components SE, C1, C2 & C3 are approaching with a mean proper motion of 23.6 ± 0.5 mas d^{-1} . Component NW is receding with a mean proper motion of 10.0 ± 0.5 mas d^{-1} and corresponds to the same ejection event which produced approaching component SE. For an estimated distance to the source of 11 kpc the approaching components have an apparent transverse velocity of $1.5c$. Assuming an intrinsically symmetric ejection and the standard model for apparent superluminal motions, we derive an intrinsic bulk velocity for the ejecta of $0.98^{+0.02}_{-0.05}c$ at an angle to the line of sight of 66 ± 2 degrees (at 11 kpc). The ejections occurred after a 20-day ‘plateau’ during which the X-ray emission was hard and stable and the radio had an inverted spectrum. The first two ejections were punctuated by four days of rapid radio oscillations, indicative of an unstable inner accretion disc being repeatedly ejected [14,38,34,8,16]. The apparent curvature of the jet is probably real, although the cause of the bending is uncertain. A detailed presentation and discussion of these results may be found in [18].



1915+105 (Fig 2; [18]) the derived bulk Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$, under the assumption of an intrinsically symmetric ejection, is 1.8 at 9 kpc (a likely lower distance to the source), 2.6 at 10 kpc, and asymptotically approaches infinity at 11.2 ± 0.8 kpc (the derived upper limit to the distance). This large uncertainty in γ , and its sensitivity to assumed distance, is illustrated in Fig 3. It seems unlikely that we are going to be able to measure the distance of the system accurately enough to place an upper limit on the Lorentz factor, so what other methods can we use?

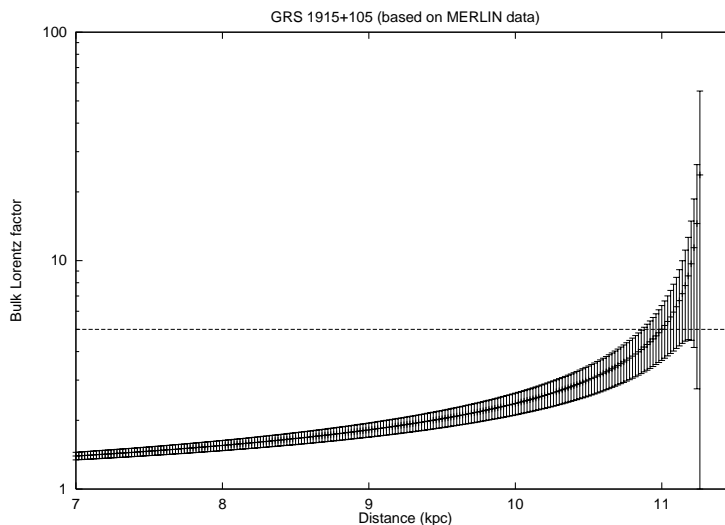


Fig. 3. The variation in derived bulk Lorentz factor for GRS 1915+105 based upon the MERLIN observations of [18]. The horizontal line corresponds to $\gamma = 5$ (the solution for a distance of 11 kpc).

In [18] a lower limit to the energy budget of the ejecta observed from GRS 1915+105 with MERLIN was calculated (based upon several assumptions which are outlined in the paper), and it was shown that, at a distance of 11 kpc, the minimum power requirement for generation of internal energy, assuming the primary ejection was generated in ~ 12 hr, was 4×10^{38} erg s^{-1} . This power requirement increases by a factor of four when multiplied by $(\gamma - 1)$ to account for the kinetic energy, and by a further factor of two if there is a cold proton for each electron. Thus the total power requirement is of order the Eddington luminosity for a $10M_{\odot}$ black hole.

Based upon the equations presented in [18] it can be shown that the total power (internal + kinetic), $P \propto \gamma^r$, where $r \sim 3.5$ (for discrete ejections and a spectral index ~ -0.8). The dependence of the total mass of protons on γ is weak and so we do not consider it here. Assuming that the black hole

in GRS 1915+105 cannot generate more than $10^{42} \text{ erg s}^{-1}$, we can derive a maximum Lorentz factor of ~ 30 . A more conservative limit on the power of $10^{41} \text{ erg s}^{-1}$ leads to a maximum Lorentz factor of ~ 15 .

So we find that the bulk Lorentz factor for GRS 1915+105 alone can only be constrained with any confidence between 1.4 ($\beta = 0.7$) and 30 ($\beta = 0.9995$!), with even these numbers based upon several assumptions. For the other highly relativistic jet sources (in particular GRO J1655-40, but also probably XTE J1748-288 and Cyg X-3) the data are arguably even less constraining than they are for GRS 1915+105. In addition, only for SS 433 is there strong evidence for many independent ejections having the same bulk velocity, although it is encouraging that VLBA observations of GRS 1915+105 [6] at a different epoch to our MERLIN observations [18] derive the same proper motion for the approaching component, considerably higher than the earlier VLA observations (which may have been hampered by insufficient angular resolution). This range in Lorentz factor is similar to the range inferred for AGN (e.g. [46]) from VLBI imaging, although lower than the very high values of γ (up to 100) apparently required to explain some AGN rapid variability (e.g. [47]). Note that under the assumption that $\gamma \sim 2.5$ for GRS 1915+105 and GRO J1655-40 (i.e. before the more recent MERLIN and VLBA results), models have already been developed to explain why jets from X-ray binaries have a lower terminal velocity than those from AGN [29,41]. It would clearly be of great importance to determine the distance of a superluminal source to be significantly less than the maximum allowed (for $v = c$) and thereby place an upper limit on γ .

3 The disc : jet coupling

One of the most active areas of study over the past couple of years has been the relation between the accretion disc (the X-ray source) and the jet (the radio source). In many, maybe all, systems, some dramatic change in the jet (whether inferred from radio emission or directly imaged), is found to have a corresponding event in X-rays. This link between X-ray state changes and radio emission was noted already by [24].

On the most general level, it is found that most bright X-ray transients, including the classical soft X-ray transients (SXTs) such as A0620-00, are accompanied during X-ray outburst by a radio outburst (see e.g. [24,27]). Since these outbursts are believed to result from rapid increases in mass accretion rate onto the compact object as a result of a disc instability, it is clear in this instance that a significant change in the accretion disc structure and mass accretion rate are coupled to the production of a radio event. It seems very likely that such events correspond to ejections of plasmons, possibly at relativistic velocities [27], although an outflow from a ‘classical SXT’ (if such a thing really exists) has yet to be unambiguously resolved.

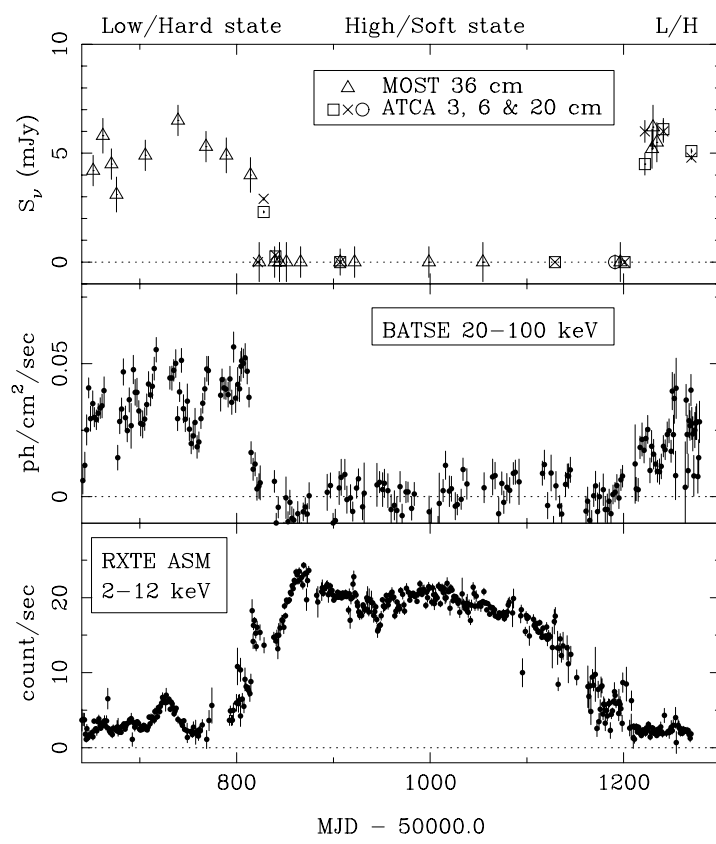


Fig. 4. Radio, hard- and soft-X-ray monitoring of GX 339-4 before, during and after the 1998 high/soft state. The radio emission is reduced by more than a factor of 25 during this state. Unusually optically thin emission ($S_\nu \propto \nu^{-0.4}$) is observed just before and after the state changes, probably corresponding to discrete ejection events. From [19].

In the case of the more persistent BHC systems, Cyg X-1 and GX 339-4, amongst the best candidates for quasi-continuous weak jets (see below), two effects indicate a strong disc : jet coupling. Firstly, the X-ray and radio emission are correlated on long (\geq days) timescales during the most common low/hard X-ray state [22,39], including during brief periods of flare-like activity in Cyg X-1 [39,4]. Secondly and more dramatically, the radio emission abruptly drops below detectable levels (by a factor of ≥ 25 in the case of GX 339-4) during transitions to high(er)/soft(er) states (Fig 4; [3,19]). Such state transitions are believed to physically correspond to major changes in the geometry and relative importance of the inner accretion disc and Comptonising corona, and it is clear that the low/hard state generates a flat-spectrum, per-

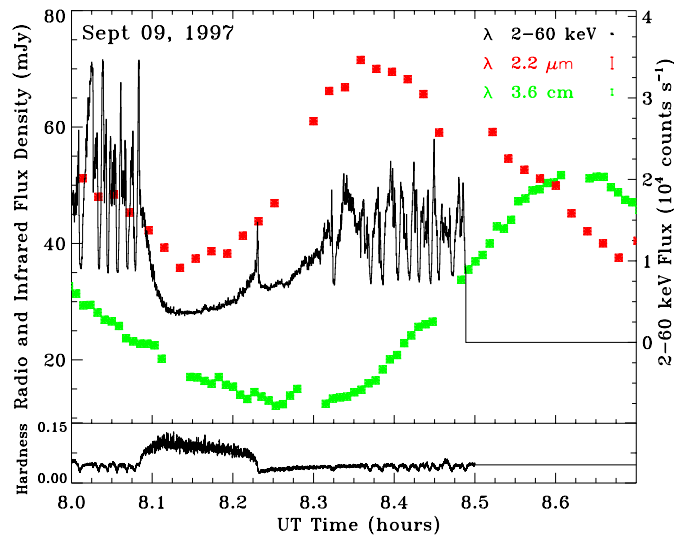


Fig. 5. Simultaneous X-ray, infrared and radio observations of GRS 1915+105. Following a dip in the X-rays (around UT = 8.1 hr), modelled as the disappearance of the inner 100 km or so of the accretion disc, the infrared rises and is followed shortly thereafter by a rise in the radio emission with the same pulse shape. This is interpreted as ejection of some fraction of the inner accretion disc and subsequent observation of synchrotron emission from cm – μ m wavelengths from the new plasmon. Figure from [34]; see also [14,38,8,16].

sistent radio source, which is likely to be a conical quasi-steady jet, whereas the high(er)/soft(er) states do not [19]. Whether the high(er)/soft(er) states simply do not generate an outflow, or whether the radio emission is quenched in some way (e.g. via Compton cooling by a much increased density of soft X-ray photons) is unclear at present.

Perhaps the most dramatic example of disc : jet coupling has been in GRS 1915+105, in which radio – infrared oscillations with periods of 10 – 60 min have been found to follow X-ray dips (see Fig 5). These radio – infrared oscillations have been interpreted as synchrotron emission from repeated small ejections suffering strong adiabatic expansion losses [14,38,8,34,16], while the X-ray dips have been interpreted as the repeated disappearance of the inner (\sim few 100 km of the) accretion disc [1]. The obvious conclusion to be drawn is that some of the inner disc is being accelerated and ejected away from the system. The fraction of the accretion rate which is ejected has been estimated at roughly 10% [16] but the uncertainties in this calculation, due to incomplete knowledge of the spectrum, size, filling factor of the ejecta and the comparative reality of numbers derived from X-ray spectral fits, etc., are

very large. Still, it is of great interest to know whether or not black holes remove the majority of matter that they attract from the Universe, or whether they spit it back at relativistic velocities!

In addition to a soft X-ray (disc) : radio (jet) coupling, there is also clearly a related hard-X-ray – radio coupling (e.g. Fig 4; [19] and references therein). In particular broad-band hard X-ray emission (i.e. 20–100 keV) as observed with GRO/BATSE is very well correlated with radio emission in many cases. It is currently believed that the hard X-ray emission is a result of inverse Compton scattering of lower-energy photons by a corona of high-energy electrons (e.g. [40]). Given that both the jet and the corona are inferred to arise in the vicinity of the inner accretion disc, the *inferred* composition of the corona as being a population of high-energy electrons, and the *observed* transport of relativistic electrons by the jet (we estimated a mean Lorentz factor for the synchrotron-emitting electrons of 240 for the ejections from GRS 1915+105 observed with MERLIN), it seems that the corona and jet must be inextricably linked. In both [40] and [19] it is suggested that the corona is simply the base of the jet; however Comptonisation modellers have yet to take this suggestion seriously and incorporate it into the geometries and bulk dynamics of their models. While it seems likely that the high-energy electrons responsible for the synchrotron emission are simply the high-energy (nonthermal) tail of the same energetic population of electrons responsible for the Comptonisation, more detailed calculations of both populations are required before we can be certain.

4 Compact, flat-spectrum cores

For a simple, single synchrotron source we expect to observe a spectral index (α , where flux density $S_\nu \propto \nu^\alpha$) of +2.5 below frequencies at which the source is self-absorbed, and in the range -0.5 to -1 at frequencies at which the source is optically thin (see e.g. [26] for more details). However, in many cases of persistent or repetitive radio emission from X-ray binaries, there appears to be an underlying flat-spectrum ($\alpha = 0$) component. During outbursts the emission is dominated by far brighter components which rapidly evolve to an optically thin state (presumably as they expand). For example, during relative quiescence Cyg X-3 shows a flat spectrum between cm – mm wavelengths [11,36], with little evidence for either high- or low-frequency cut-offs. Even more extreme, during periods of radio oscillations GRS 1915+105 appears to show a flat spectrum from cm – μ m wavelengths [14,34,16].

By analogy with AGN, it seems likely that the flat spectra of these quiescent components may originate in partially self-absorbed synchrotron emission from conical jets, with higher frequencies probing the smaller and brighter regions towards the base of the jet (e.g. [31,23,9,10]). Amongst the best examples of persistent flat spectrum cores which experience little ‘contamination’ from optically thin components, and therefore probably of continuous jets,

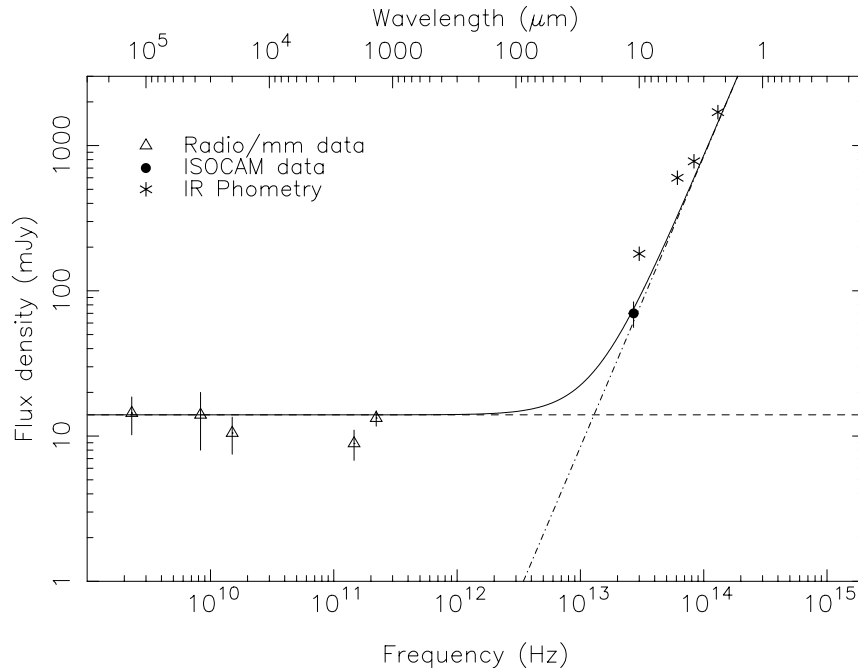


Fig. 6. Illustration of the radio–mm flat spectral component in Cyg X-1, from [20]. At wavelengths shorter than $\sim 30\mu\text{m}$ the component is swamped by thermal emission from the OB companion star. We have no clear determination of either high- or low-frequency cut offs to this spectral component, and its origin remains uncertain. Brighter, analogous flat-spectrum components observed from Cyg X-3 and GRS 1915+105 appear to extend to at least $\sim 2\mu\text{m}$.

are the persistent black hole candidates Cyg X-1 and GX 339-4 ([39,15]). In particular, in Cyg X-1 the evidence for a compact jet seems compelling:

- A flat radio spectrum [39], recently detected to extend to mm wavelengths (Fig 6; [20]).
- A $\sim 20\%$ modulation at the 5.6-d orbital period at 15 GHz, with minimum near superior conjunction of the compact object, and increasing delays and decreasing fractional modulation at lower frequencies [39,4].
- Direct imaging of structure with the VLBA [43,7].

Futhermore, the recent detection of low-level ($\sim 2\%$) linear polarisation of the radio emission from GX 339-4 [5] opens up the possibility of probing the magnetic field structure within such compact jets. Such a low level of linear polarisation was also detected from the ‘second stage’ optically thick radio component associated with the X-ray transient V404 Cyg [21]. This component also showed ‘radio QPO’ possibly similar to those observed from

GRS 1915+105 (see above) and may in fact have represented a temporary transition to a compact jet following the major outburst (as opposed to the expanding shell model proposed by [21]). Detection of a comparable level of linear polarisation from the (inferred) compact jet in Cyg X-1, and its variation with the orbital cycle, would be very interesting. The radio properties of Cyg X-1 and GX 339-4 are similar to those of the neutron star Z-sources, low-mass X-ray binaries accreting at or near to the Eddington luminosity, suggesting that these sources may also be producing quasi-stationary outflows (see below).

In addition the relation of the flat-spectrum radio-infrared oscillations of GRS 1915+105 to the (apparently) more continuous flat-spectrum jets discussed above is unclear – possibly the oscillations are some kind of intermediate state or pulsed jet. The ‘plateau’ states in GRS 1915+105 ([18] and references therein) appear to be characterised by luminous flat spectrum radio emission which may be a brighter (larger ?) version of the flat spectrum cores in e.g. Cyg X-1. If this is the case GRS 1915+105 appears to produce steady jets, pulsed jets and major (optically thin) ejections at different times.

It is important to stress that neither high- nor low-frequency cutoffs have been found in the flat-spectrum component of *any* X-ray binary. The extension of a synchrotron spectrum to high (e.g. infrared in GRS 1915+105) frequencies dramatically increases the **power** required for the generation of high energy electrons and magnetic field. The extension of the spectrum to low radio frequencies increases the **number** of electrons required, highly significant for the mass-flow rate if each electron is accompanied by a proton. It may turn out to be extremely difficult to observe such cut-offs however: in the case of Cyg X-1 for example, thermal emission will dominate the flat synchrotron spectrum at $\lambda \leq 30\mu\text{m}$ (Fig 6; [20]); in the case of GRS 1915+105 extreme optical extinction will probably preclude the discovery of the optical counterparts of the near-infrared synchrotron oscillations; and in all cases radio observations at frequencies below ~ 100 MHz are generally difficult to make.

It should be stressed that while the flat-spectrum component from X-ray binaries is reminiscent of that observed from ‘flat-spectrum’ AGN, it is in fact *much flatter* [20], with a spectral index very close to zero over several decades in frequency. So, while it is natural to try and apply the compact synchrotron-emitting jet models developed for AGN, it is by no means certain that they are relevant. At least two additional possibilities exist :

- Optically thin emission from an electron spectrum which is much harder than that observed during major outbursts [33,48]. However the frequency-dependent time delays observed in e.g. GRS 1915+105 argue against this interpretation, as they imply significant optical depth.
- (Nonthermal) free-free emission which should produce a perfectly flat spectrum. It is conceivable that this process dominates over synchrotron in the most compact and dense parts of the jet, but that during discrete

ejections, as the plasmons expand, synchrotron emission (which has a weaker dependence on the electron number density) comes to dominate.

Important future observations will include discovery of high- or low-frequency cutoffs in the flat spectral component, variability timescales and measurements of polarisation.

5 Black holes and neutron stars

The majority of the highly relativistic Galactic jet sources potentially (perhaps even probably) contain black holes. Furthermore, a more thorough survey of the literature reveals that it is the BHC X-ray transients which are most likely to be accompanied by strong radio outbursts. While some neutron star transients have also produced radio outbursts, e.g. Aql X-1 (at least once) and Cen X-4 [24], no transient which has been demonstrated unequivocally to harbour a neutron star has ever matched the very bright (≥ 1 Jy) radio flux densities recorded from BHC transients such as V404 Cyg and GRO J1655-40.

The brightest radio source associated with a neutron star in an X-ray binary is that of Cir X-1. One of the persistently brightest X-ray sources in the sky (although with a quite dramatically changing X-ray light curve – [44]), in the 1970s Cir X-1 was detected as a ≥ 1 Jy radio source, with outbursts periodic at the 16.6-day orbital period. However, since that time the radio source has weakened considerably, and at present the radio core is detected at ≤ 10 mJy with more flux at lower frequencies arising in the complex surrounding synchrotron nebula [42]. Within this nebula collimated arcmin-scale structures are evident, aligned with which is an arcsec-scale asymmetric jet [42,17] (Fig 7). Naively interpreting the asymmetry of the jet as relativistic aberration of an intrinsically symmetric ejection (or, more likely, multiple ejections), a velocity for the outflow of $\geq 0.1c$ was derived. Further observations to confirm that this structure is dynamic, and hopefully to track its expansion and hence directly measure outflow velocities, are very important in seeking to establish whether or not neutron stars can also produce highly relativistic outflows. Recent VLBA observations of another neutron star source, Sco X-1, have also revealed strong evidence for an outflow [2]. It is interesting to note that several authors (e.g. [30]) have suggested that the velocity of jets from neutron star X-ray binaries (a class in which SS 433 and Cyg X-3 were often included without any clear justification) would always be $\sim 0.3c$ and those from black holes would always be $\geq 0.9c$, this dichotomy reflecting the escape speed from near the surfaces of these two types of objects (supported as a concept by the velocities observed from protostars and white dwarfs). It seems that within the next couple of years we will be in a position to directly test this assertion.

Beyond transient and unique sources, three clear classes of persistently bright neutron star X-ray binaries exist, the Z and Atoll sources [45] and

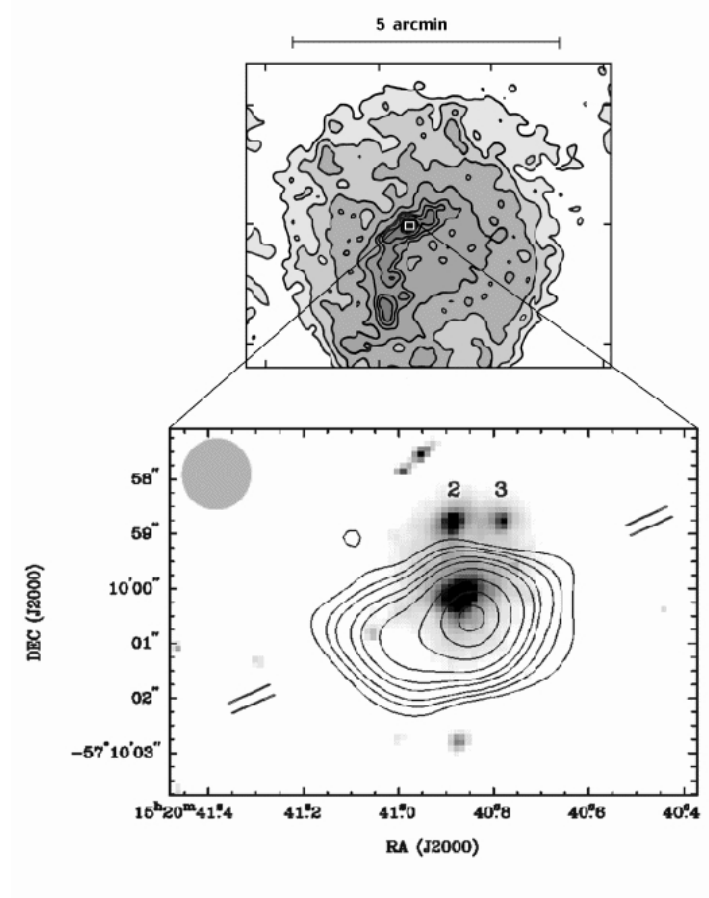


Fig. 7. An asymmetric arcsec-scale radio jet from the neutron star X-ray binary Cir X-1. The arcsec-scale jet aligns with larger scale collimated structures in the surrounding nebula, implying transport of matter from the binary to regions over a parsec away. The asymmetry of the jet, if due to Doppler boosting of an intrinsically symmetric outflow, indicates bulk motion at $\geq 0.1c$. From [17].

X-ray pulsars [49]. The Z and Atoll sources are believed to contain low ($B \leq 10^{10}$ G) magnetic field neutron stars, the X-ray pulsars much higher field ($B \geq 10^{11}$ G) neutron stars. The Z sources are accreting near the Eddington limit and include Sco X-1 and possibly also Cir X-1 (although the latter is still unique in many respects). While faint (mostly lying at distances ≥ 8 kpc) their radio properties appear to be very similar to those of the BHCs GX 339-4 and Cyg X-1, discussed above. Combined with the direct imaging evidence for outflows from Sco X-1, this suggests that the Z sources also have weak jets. The Atoll sources, which have timing properties similar to the BHCs are *not*

in general observed as radio sources; only GX 13+1 is confirmed as a bright radio emitter (and may in fact be a hybrid Z/Atoll source). No strong-field X-ray pulsar systems have ever been detected as radio synchrotron sources and it seems likely that they do not produce jets, probably as a result of disruption of the inner accretion disc by the strong field of the neutron star [12].

Future careful comparisons of the nature of radio emission from the various populations of neutron stars with different magnetic fields, and with the black holes, may give us fundamental clues to the puzzle of jet formation (is a high accretion rate and a weakly magnetised compact object all that is required?).

6 Conclusions

In this review I have attempted to summarise the state of some particular problems in observational research into relativistic outflows from neutron stars and black holes in X-ray binary systems. I have been able to do no more than sketch an outline of the work going on in this exciting field and, due to space limitations, have been forced to omit several major areas which deserve full discussions on their own. Significantly among these are the fundamental questions of jet structure (continuous or discrete?), jet composition ($e^-:e^+$ or $e^-:p^+$?) and the physics of jet formation!

Much work remains to be done in this field, and it is this author's (by no means original!) feeling that jets will turn out to be ubiquitous wherever there is an (inner) accretion disc and a high (approaching Eddington?) accretion rate. The sooner that the coupled disc:jet system is considered as a single entity and not as two distinct problems by the high and low(er) energy communities respectively, the better.

I have no hesitation in recommending the excellent volumes 'Beams and Jets in Astrophysics' [25] and 'X-ray binaries' [28] as reference points for much of the theory and observational data presented in this review.

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